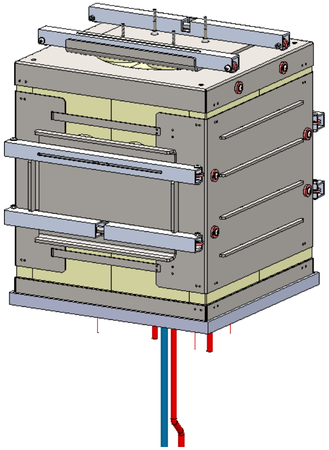
Super High-efficiency Integrated Fuel-cell and Turbomachinery - SHIFT

PI: Yuto Takagi, Saint-Gobain

Project Vision

- Saint-Gobain offers a unique all-ceramic SOFC technology for low-cost, high durability systems, enabling no stack replacement over system life
- We are scaling-up both the module size and the production rate to meet design and cost requirements
- Modular SOFC hotbox capable of pressurized operation, and system integration with rotary screw engines



SAINT-GOBAIN PCI Precision Combustion, Inc. Brayton Energy LLC

Project Overview

Fed. funding:	$2.9M
Length	24 mo.

Team member	Location	Role in project
Saint-Gobain (SG)	Northboro, MA	Principal Investigator (PI) High durability all-ceramic SOFC stack with low-cost manufacturing
Brayton Energy (BE)	Hampton, NH	Rotary screw compressor and expander design, system modeling
Precision Combustion (PCI)	North Haven, CT	Pressurized hotbox design and testing, Balance of Plant

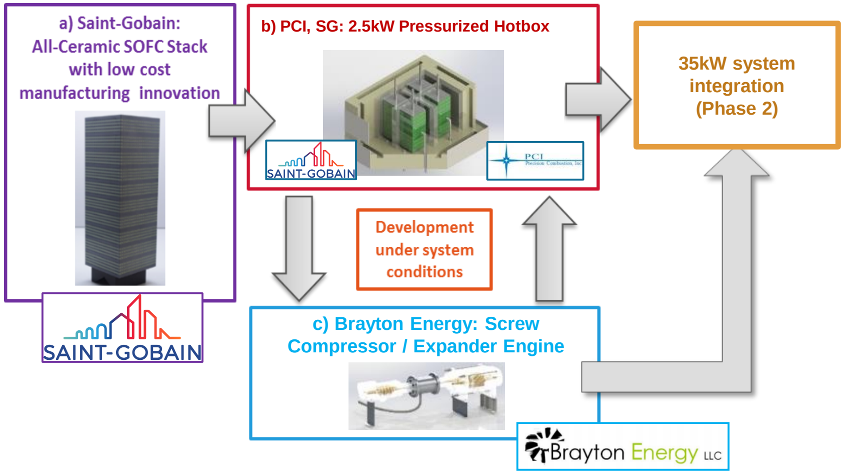
Context/history of project

- INTEGRATE SHIFT Project started August 2018
- SG has 12 years history of R&D in all-ceramic co-sintered SOFC stacks
- SG served as a PI in an ARPA-e program in high performance refractory field Currently runs/participates in multiple DOE EERE/NETL programs
- SG supplies SOFC sub-stacks to the ongoing WSU INTEGRATE program
- BE participates in an ongoing GENSETS program

Innovation and Objectives

Innovation

- World's first all-ceramic stack module at >10kW scale with very low degradation rate (< 0.15 %/kh)
- Low cost manufacturing innovation
- Pressurized hotbox for high efficiency operation
- Rotary screw engine system that allows improved pressure controllability



Task outline, technical objectives

- Low cost SOFC production processes
  - Ceramic component extrusion
  - High throughput machining process
- Pressurized 2.5 kW stack-reformer integrated hot box demonstration
- Customized screw engine and components design

Tech-to-Market objectives

- Work with advisory board members Microsoft, Cummins, UC Irvine to identify market dev. strategy
- First entry: Data centers, commercial buildings
- Scale-up plan for all-ceramic SOFC manufacturing

Saint-Gobain's SOFC Solution

Eliminates sources of failure and cost found in competing technologies

Primary SOFC Issues	Saint-Gobain Solution

1. Durability & Reliability

Primary SOFC Issues

- Cr poisoning from metal components
  → Cathode degradation
- Metal oxidation
  → Interfacial resistance increase
- Metal - ceramic sealing
  → Failure of glass seals at thermal cycles

Saint-Gobain Solution

- No Cr source (metal component) in the stack
  → No internal Cr poisoning
  → Enabled by SG novel ceramic interconnects
- No metal interface in the stack
  → No interfacial resistance increase
  → Enabled by SG novel ceramic interconnects and multi-cell co-firing technology
- No metal-ceramic sealing required
  → All materials designed to be in a close CTE range

2. Cost

Primary SOFC Issues

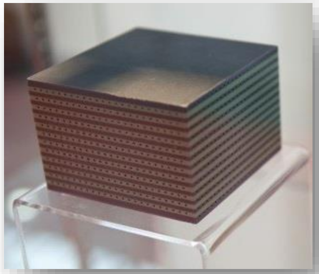
- High grade metal interconnects + conductive protection coatings
- Multi-step firing process
- Complex stack assembly

Planar Design

Saint-Gobain Solution

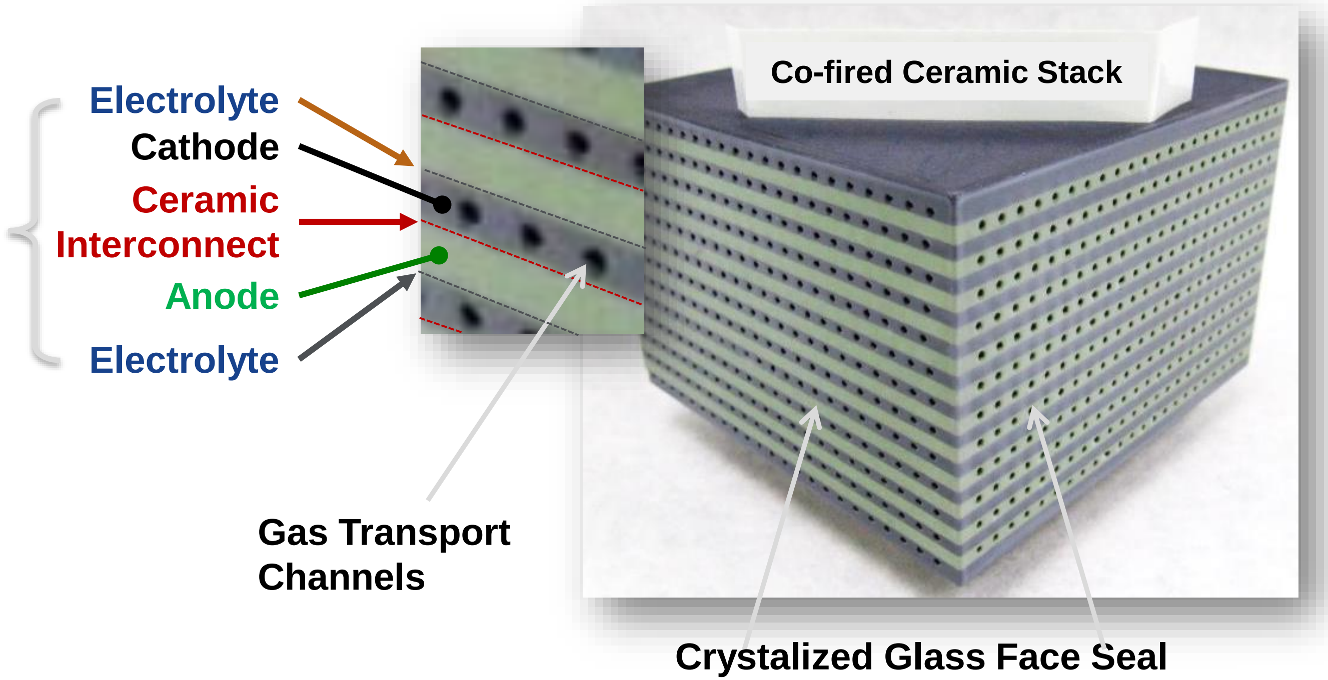
- Novel ceramic interconnect
  → Removed expensive metals and their coatings
- Multi-cell processing and co-firing
  → Simple green assembly + co-firing
  → Optimized microstructure + material sets
  → Stack level glass seal

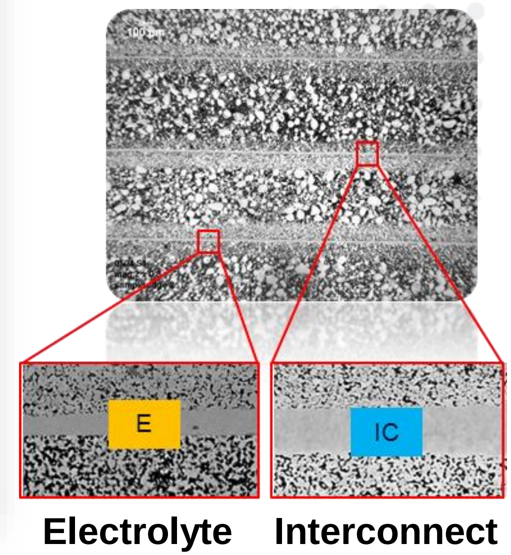
SG All-Ceramic Design



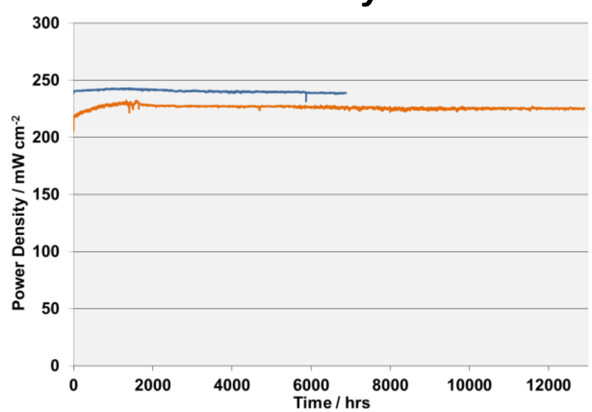
Saint-Gobain's Innovative All-Ceramic Concept

Monolithic design achieved by state-of-the-art co-firing process and surface glass seal

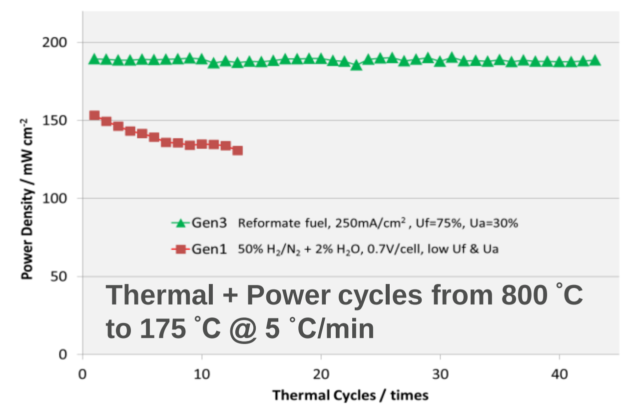




Long term durability
< 0.2 %/khrs,
> 10,000 hrs



On/off
> 40 cycles



All-Ceramic SOFC: Historical Perspective

Stack size / production scale-up and co-developments in progress

2005 ~ 2010
Technology development

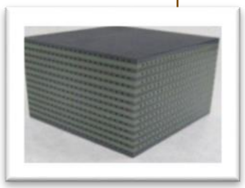
2011 ~ 2013
Scale, output & durability

2014 ~
Co-development with customers and partners

2005
Internal project started, material and process development

2009
'Button Stack' developed with all relevant features

2010-2011
Scale-up, performance and degradation improvements



2013
Degradation rate of <0.2%/khr demonstrated

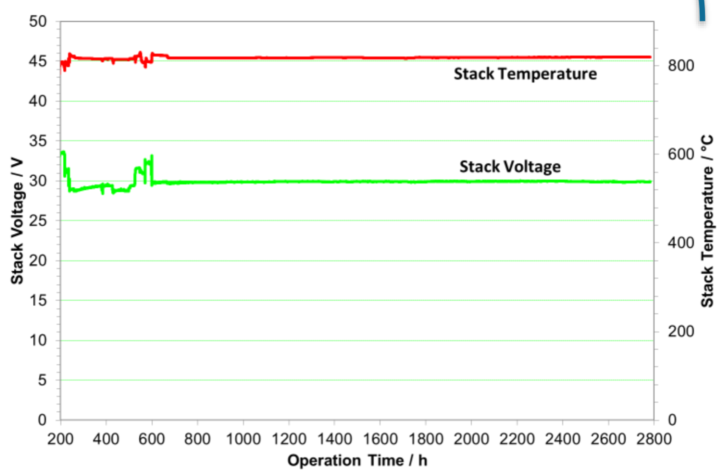
2014
150W module for testing developed

2016
24-Cell stack

2017-2018
40-Cell stack and hot box

600W Hotbox stable operation demonstrated with an all-ceramic stack

- ❑ 3,000 hours of stable operation with no discernable degradation
- ❑ Stable temperature and stack performance

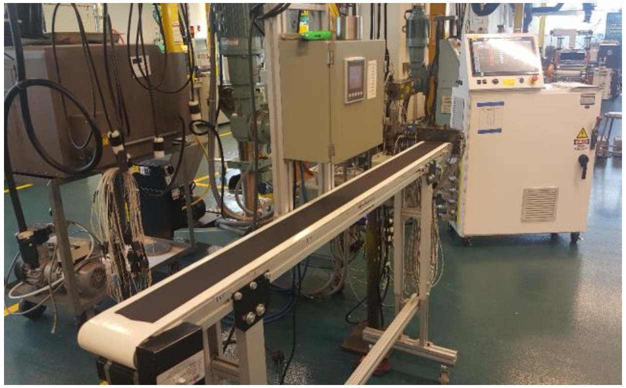


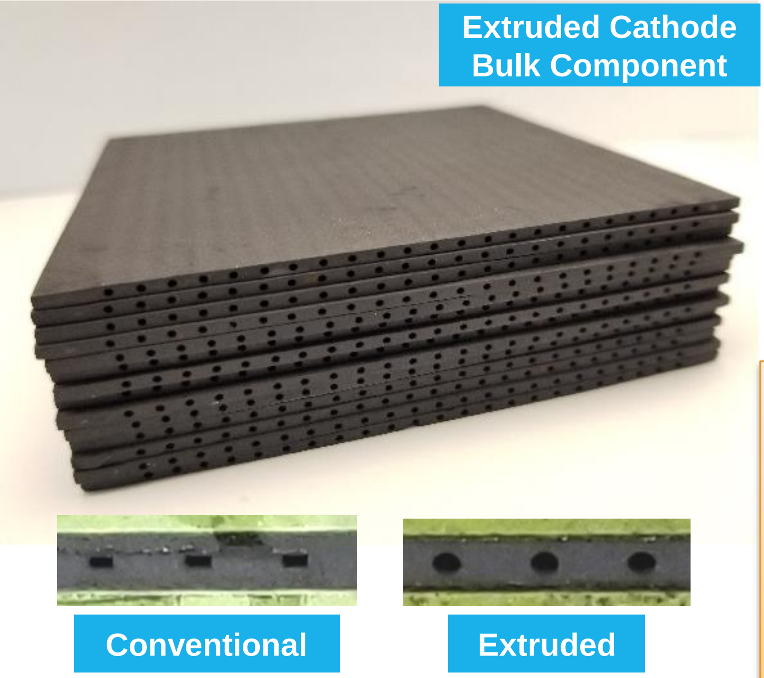
Task 3: Stack Manufacturing Innovation – Ceramic Extrusion

Cathode component extrusion process qualified

A robust compounding + extrusion process and a binder formulation were developed to produce cathode components with > 80% yield

- ❑ No cracks observed before or after sintering trials
- ❑ All samples met the pre-defined specs





Property	Pass/Non pass
X-Y dimensions (mm)	Pass
Z dimensions (mm)	Pass
Camber (µm)	Pass
Flatness – FLTq (µm)	Pass
Porosity %	Pass
Strength (MPa)	Pass

Related Milestones:
M3.1.1 Extruded AB component meets manufacturing criteria
M3.1.3 Substack with extruded components meet manufacturing targets
M3.1.4 Substack with extruded components meet performance target

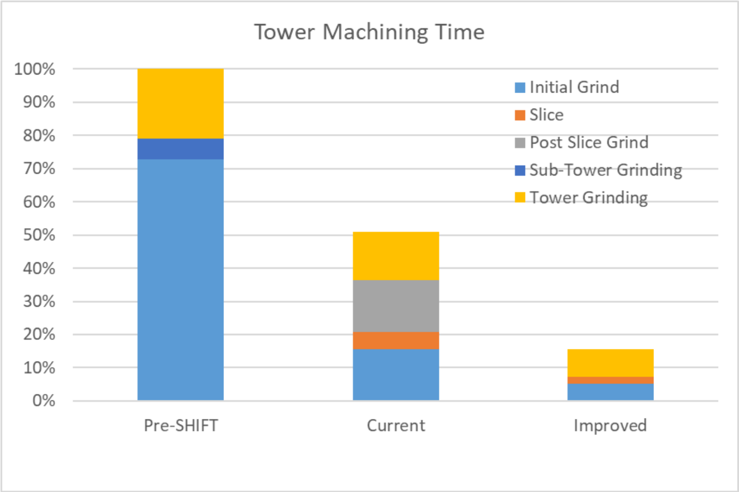
Next steps:
1. Complete anode bulk component qualification
2. Fabricate and test sub-stacks with extruded components

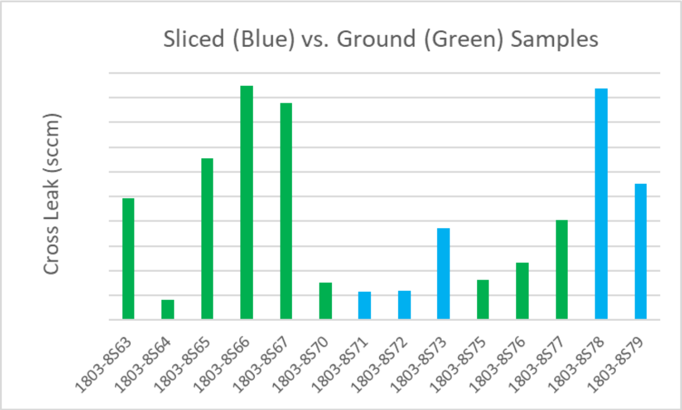
Task 3: Stack Manufacturing Innovation – High Speed Machining

Slicing process qualified cutting down the machining time to less than half

Sliced stacks achieved leak levels equivalent to the best ground stacks

- ❑ Slicing saved 50% of the stack machining time
- ❑ Additional saving possible with further process optimization





Related Milestones:
M3.1.4 Substack with extruded components meet performance target

Next steps:
1. Further optimize the slicing process to reduce machining time
2. Fabricate and test sub-stacks applying high speed machining

CHANGING WHAT'S POSSIBLE

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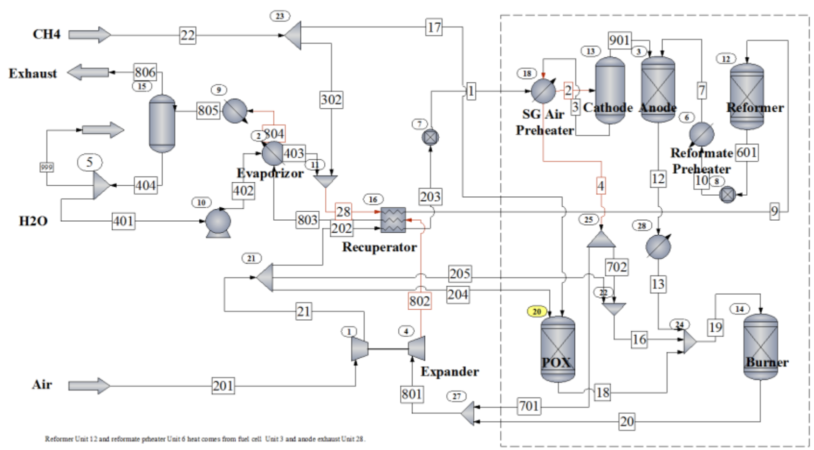
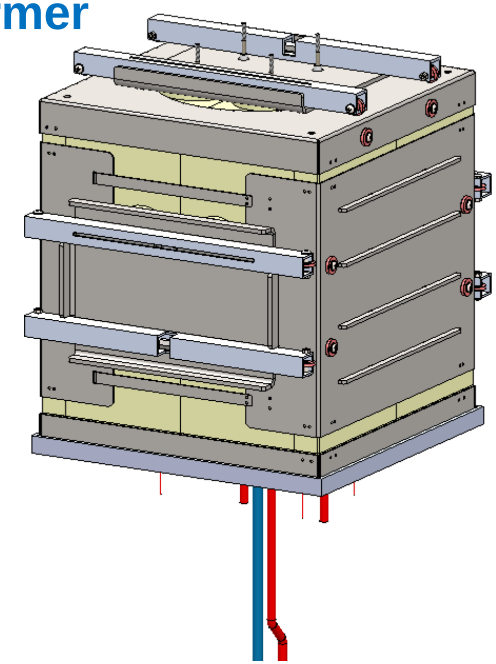
Task 4: Multi-stack Hotbox Innovation – Reformer Integration

Multi-stack hotbox design review completed with reformer integration

2.5kW Hotbox design completed with an integrated reformer

- ❑ Largely benefits from the SG 600W hotbox success
- ❑ System PFD developed and hotbox efficiency modeled
- ❑ Thorough Design review with FMEA analysis completed in June





	Cases 1-4	Case 5	Case 6
Fuel utilization	75%	77%	75%
Cell voltage	0.881	0.853	0.822
CH4 in reformate	10%	10%	10%
Maximum Temperature	825C	825C	775C
S/C ratio	2	2	2.1
Calculated system efficiency	68.4%	69.6%	69.4%

Related Milestones:

M4.1.1 Conceptual design of 2.5kW hotbox meets efficiency standard ✓

M4.3.1 Complete design of 2.5kW hotbox, final design review ✓

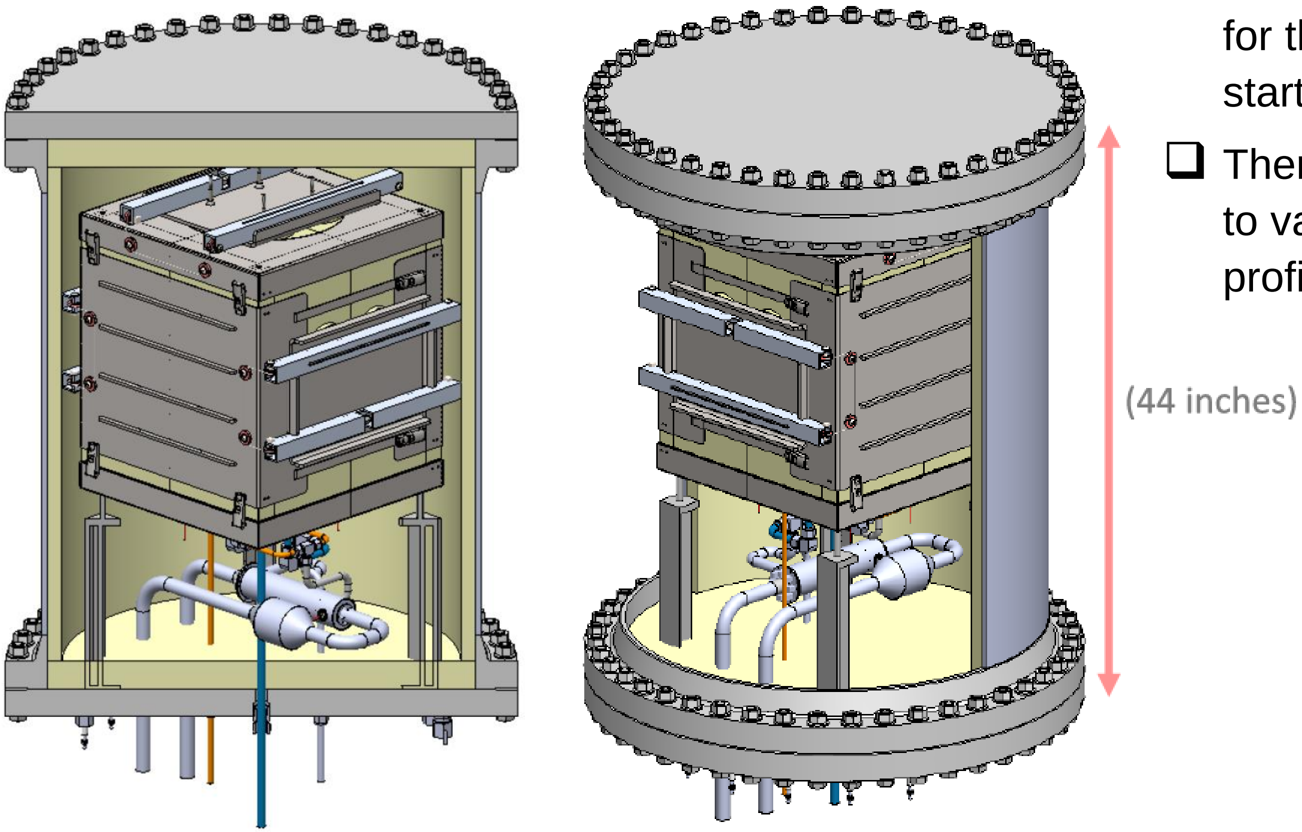
Next steps:

1. Order parts / assembly, fitness check
2. Hotbox heat-up test with thermal stacks

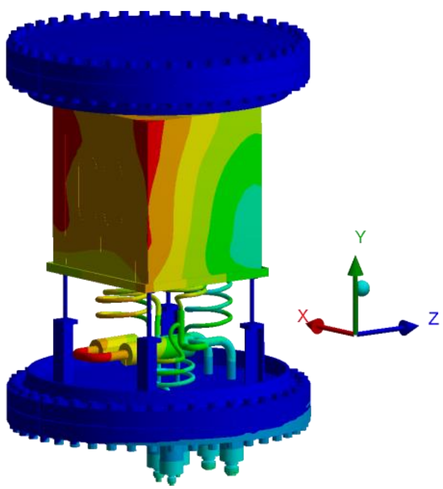
Task 4: Multi-stack Hotbox Innovation – Pressurized Design

Pressurized vessel designed and thermal modeling completed

Pressurized design reviewed as a part of the 2.5kW Hotbox DR



- ❑ Pressure vessel designed for the stack hotbox and start-up fuel processor
- ❑ Thermal modeling ongoing to validate temperature profile of the hotbox



Task 5: Hybrid Engine Specifications Defined

System modeling completed with off-design analysis

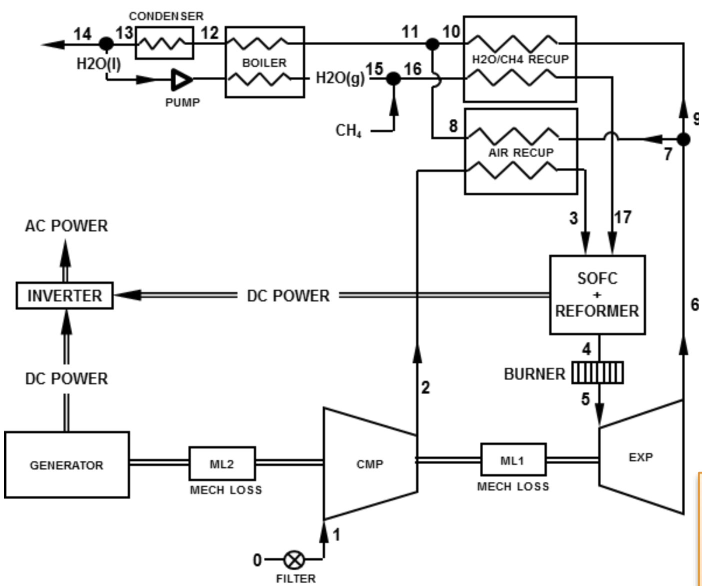
System model predicts ~70% efficiency at 30kW level

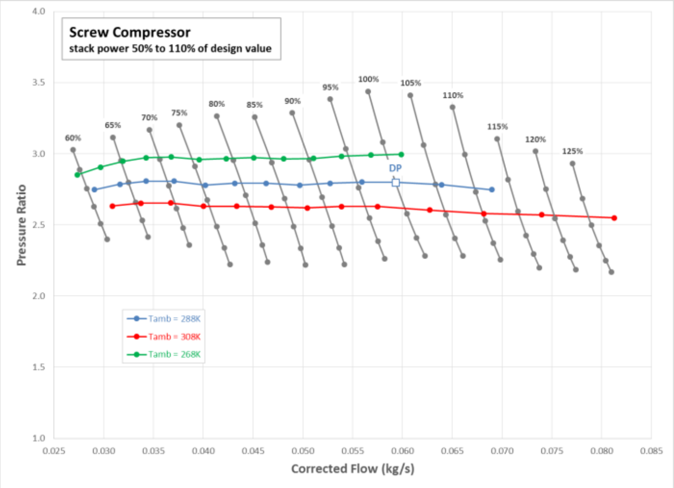
- ❑ Fuel utilization set conservatively at 75 %
- ❑ Screw engine operation conditions defined, stable pressure ratios modeled
- ❑ Preliminary cost estimated

SOFC	
DC power	30kWe
Fuel utilization	75.0%
Oxidant utilization	22.3%
Thermal loss	1.20kWt
Cell Voltage	0.822V

Engine	
Shaft power	6.38kWs
DC power	6.18kWe
Pressure ratio	2.80
Compressor massflow	0.059kg/s
Compressor efficiency	79.0%
Expander efficiency	77.0%
Generator efficiency	97.0%

System	
DC power	36.2kWe
AC power	35.1kWe
Inverter efficiency	97.0%
Condenser heat rejection	17.0kWt
Fraction H2O expelled	43.1%
LHV AC electrical efficiency	**69.4%**





Related Milestones:
M5.1.1 Down-select and issue engine specifications ✔
M5.1.2 Preliminary design review

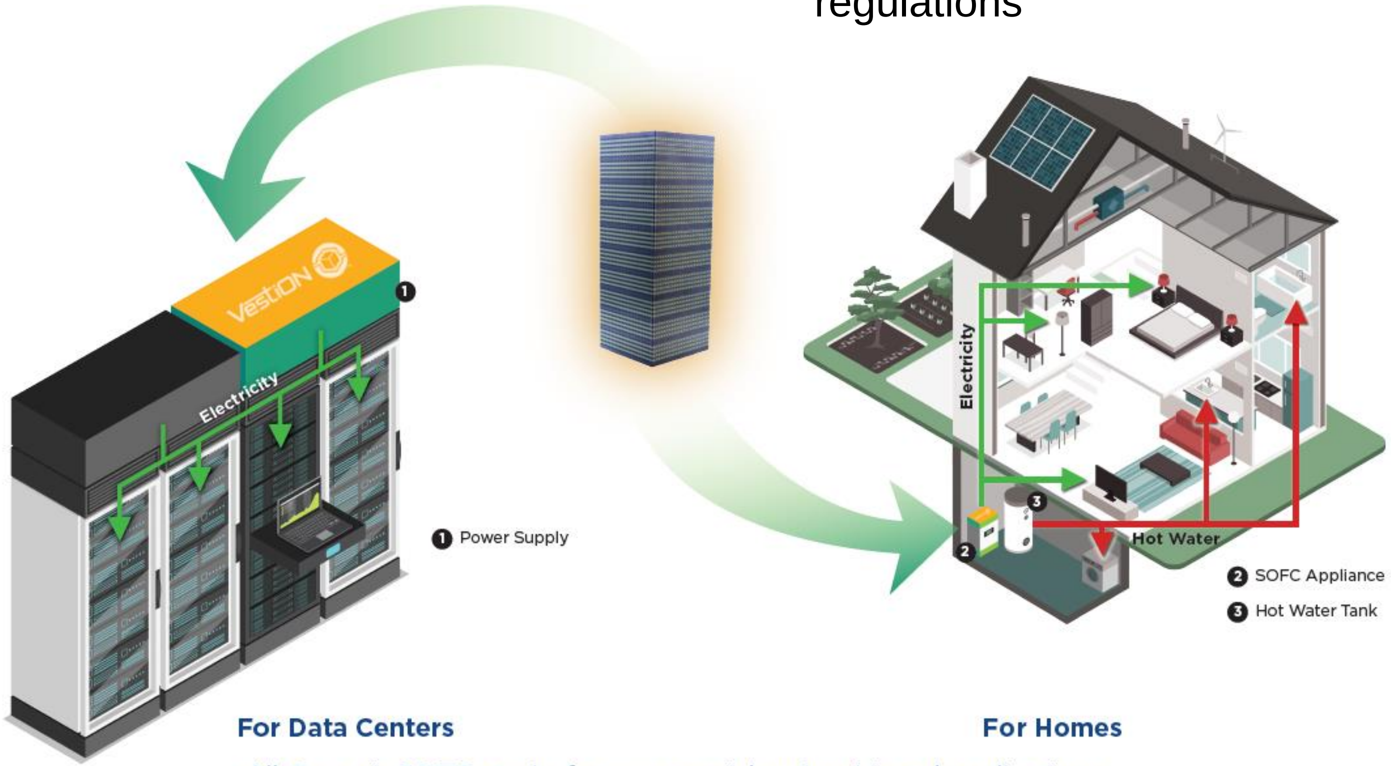
Next steps:
1. Component design and prelmiinary design review

Market Applications

Near term potentially attractive markets are Datacenters and Small Commercial buildings

Datacenters
- ❑ Direct DC power supplies for rack(s)

Homes and small commercial buildings
- ❑ Markets with government supports and/or regulations



All-Ceramic SOFC stacks for commercial and residental applications.

Potential Risks

List of potential upcoming risks in Phase 1:

- ❑ Stacks made with ceramic extrusion components do not meet quality standards
- ❑ Anode bulk component extrusion requires further development work
- ❑ Lead time of the hotbox components
- ❑ Pressure balance control during initial hotbox testing
- ❑ Stack / reformer temperature profile management in the 4-stack hotbox